

Measurement of the centrality dependence of J/ψ yields and observation of Z production in lead-lead collisions with the ATLAS detector at the LHC

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Abstract

Using the ATLAS detector, a centrality-dependent suppression has been observed in the yield of J/ψ mesons produced in the collisions of lead ions at the Large Hadron Collider. In a sample of minimum-bias lead-lead collisions at a nucleon-nucleon centre of mass energy $\sqrt{s_{NN}} = 2.76$ TeV, corresponding to an integrated luminosity of about $6.7 \mu\text{b}^{-1}$, J/ψ mesons are reconstructed via their decays to $\mu^+\mu^-$ pairs. The measured J/ψ yield, normalized to the number of binary nucleon-nucleon collisions, is found to significantly decrease from peripheral to central collisions. The centrality dependence is found to be qualitatively similar to the trends observed at previous, lower energy experiments. The same sample is used to reconstruct Z bosons in the $\mu^+\mu^-$ final state, and a total of 38 candidates are selected in the mass window of 66 to 116 GeV. The relative Z yields as a function of centrality are also presented, although no conclusion can be inferred about their scaling with the number of binary collisions, because of limited statistics. This analysis provides the first results on J/ψ and Z production in lead-lead collisions at the LHC.

Keywords: ATLAS, LHC, Heavy Ions, J/psi, Z Boson, Centrality dependence

1. Introduction

The measurement of quarkonia production in ultra-relativistic heavy ion collisions provides a potentially powerful tool for studying the properties of hot and dense matter created in these collisions. If deconfined matter is indeed formed, then colour screening is expected to prevent the formation of quarkonium states when the screening length becomes shorter than the

quarkonium size [1]. Since this length is directly related to the temperature, a measurement of a suppressed quarkonium yield may provide direct experimental sensitivity to the temperature of the medium created in high energy nuclear collisions [2].

The interpretation of J/ψ suppression in terms of colour screening is generally complicated by the quantitative agreement between the overall levels of J/ψ suppression measured by the NA50 experiment at the CERN SPS [3] ($\sqrt{s_{NN}} = 17.3$ GeV) and the PHENIX experiment at RHIC [4] ($\sqrt{s_{NN}} = 200$ GeV). Data from proton-nucleus and deuteron-gold collisions also show decreased rates of J/ψ production [5], indicating that other mechanisms may come into play. Finally, there exist proposals for J/ψ *enhancement* at high energies from charm quark recombination [6]. Measurements at higher energies, with concomitantly higher temperatures and heavy quark production rates, are clearly needed to address these debates with new experimental input. The production of Z bosons, only available in heavy ion collisions at LHC energies, can serve as a reference process for J/ψ production, since Z 's are not expected to be affected by the hot, dense medium, although modifications to the nuclear parton distribution functions must be considered [7].

The LHC heavy ion program, which commenced in November 2010, offers an opportunity to measure J/ψ and Z production in nuclear collisions at the highest energies ever achieved. The ATLAS detector provides excellent muon detection capabilities down to momenta of about 3 GeV, and J/ψ mesons and Z bosons can be readily detected via their decays to $\mu^+\mu^-$ final states. This Letter presents the first measurements of the relative yields of J/ψ meson and Z boson decays in lead-lead collisions at a nucleon-nucleon center of mass energy of $\sqrt{s_{NN}} = 2.76$ TeV. The yields are measured in four bins of collision centrality, and the variation of the yields with centrality is compared to the dependence expected if hard scattering processes scale according to expectations from nuclear geometry. No attempts are made to account for “normal nuclear suppression” [3], nor for feed-down of J/ψ from higher mass charmonium states or B hadron decay.

2. Di-muon event selection

Muons are measured by combining independent measurements of the muon trajectories from the Inner Detector (ID) and the Muon Spectrometer (MS). A detailed description of these detectors and their performance in proton-proton collisions can be found in Refs. [8, 9]. The ID volume is within

the 2 T field of a superconducting solenoid, and measures the trajectories of charged particles in the pseudorapidity region $|\eta| < 2.5$ ¹. A charged particle typically traverses three layers of silicon pixel detectors, eight silicon strip sensors (SCT detector) arranged in four layers of double-sided modules, and a transition radiation tracker composed of straw tubes. The MS surrounds the calorimeters and provides tracking for muons with $|\eta| < 2.7$ and triggering in the range $|\eta| < 2.4$. The muon momentum determination is based on three stations of precision drift chambers that measure the trajectory of each muon in a toroidal magnetic field produced by three air-core toroids. In order to reach the MS, muons have to cross the electromagnetic and hadronic calorimeters, losing typically 3 to 5 GeV of energy, depending on the muon pseudorapidity. The calorimeters efficiently absorb the copious charged and neutral hadrons produced in lead-lead collisions.

The trigger system has three stages, the first of which (Level-1) is hardware based. The Level-1 minimum-bias trigger uses either the two sets of Minimum-Bias Trigger Scintillator (MBTS) counters, covering $2.1 < |\eta| < 3.9$ on each side of the experiment, or the two Zero-Degree Calorimeters (ZDC), each positioned at 140 m from the collision point, detecting neutrons and photons with $|\eta| > 8.3$. No muon-specific triggers were used to select the data presented here. The MBTS trigger was configured to require at least one hit above threshold from each side of the detector. A Level-2 timing requirement on a coincidence of signals from the MBTS was then imposed to remove beam backgrounds. The trigger efficiency was studied using an independent trigger probing random filled bunch crossings at Level-1. For these triggers, empty events were removed by testing for a minimal level of activity in the silicon detectors. The combined trigger and event selection efficiency is discussed in section 3.2.

In the offline analysis, minimum-bias triggered events are required to have a reconstructed primary vertex, at least one hit in each set of MBTS counters, and a time difference between the sides of less than 3 ns to reject beam-halo and other beam-related background events. Measurements of the

¹ In the right-handed ATLAS coordinate system, the pseudorapidity η is defined as $\eta = -\ln[\tan(\theta/2)]$, where the polar angle θ is measured with respect to the LHC beamline. The azimuthal angle ϕ is measured with respect to the x-axis, which points towards the centre of the LHC ring. The z-axis is parallel to the anti-clockwise beam viewed from above. Transverse momentum and energy are defined as $p_T = p \sin \theta$ and $E_T = E \sin \theta$, respectively.

muon trajectories from both the ID and MS are combined, resulting in a relative momentum resolution ranging from about 2% at low momentum up to about 3% at $p_T \sim 50$ GeV. For this analysis, oppositely charged muons are selected with a minimum p_T of 3 GeV each and within the region $|\eta| < 2.5$.

The data sample consists of approximately $6.7 \mu\text{b}^{-1}$ from the 2010 LHC heavy ion run. In order to determine the $J/\psi \rightarrow \mu^+\mu^-$ reconstruction efficiency, Monte Carlo (MC) samples have been produced superimposing J/ψ and Z events from PYTHIA [10] into simulated lead-lead events generated with the HIJING [11] event generator. HIJING was run in a mode with effects from jet quenching turned off, since they have not been adjusted to agree with existing experimental data. Elliptic flow was imposed on the events subsequent to generation, with a magnitude and p_T dependence derived from RHIC data. The detector response to the complete PYTHIA+HIJING event is simulated [12] using GEANT4 [13].

Lead-lead collision centrality percentiles are defined from the total transverse energy, ΣE_T^{FCal} , measured in the forward calorimeter (FCal), which covers $3.2 < |\eta| < 4.9$. The same conventions and bins for centrality are used as in our previous publication [14]. The centrality dependence of the muon detection efficiency is parameterized as a function of the total number of hits per unit of pseudorapidity detected in the first pixel layer. This is strongly correlated to ΣE_T^{FCal} , but gives a more direct measure of the ID occupancy. The full data sample is divided into four bins of collision centrality, 40-80%, 20-40%, 10-20%, and 0-10%. The most peripheral 20% of collisions are excluded from this analysis due to larger systematic uncertainties in estimating the number of binary nucleon-nucleon collisions in these events.

The $J/\psi \rightarrow \mu^+\mu^-$ reconstruction efficiency is obtained from the MC samples as a function of the event centrality. The inefficiency gradually increases from peripheral to central collisions, due primarily to an occupancy-induced inefficiency in the ID tracking, as shown in Table 1. The $Z \rightarrow \mu^+\mu^-$ reconstruction efficiency is obtained in a similar way.

An example of the very good agreement between data and MC in different centrality bins is presented in Figure 1, which shows the numbers of Pixel and SCT hits associated to tracks selected with a looser $p_T > 0.5$ GeV cut than that for the J/ψ . The figure shows results for data and MC at two different centralities (0-10% and 40-80%). The distributions of the number of hits averaged over η and the average number of hits as a function of η are shown. The slight decrease of the number of SCT hits on track as a function of centrality is well reproduced by the simulation, demonstrating that the

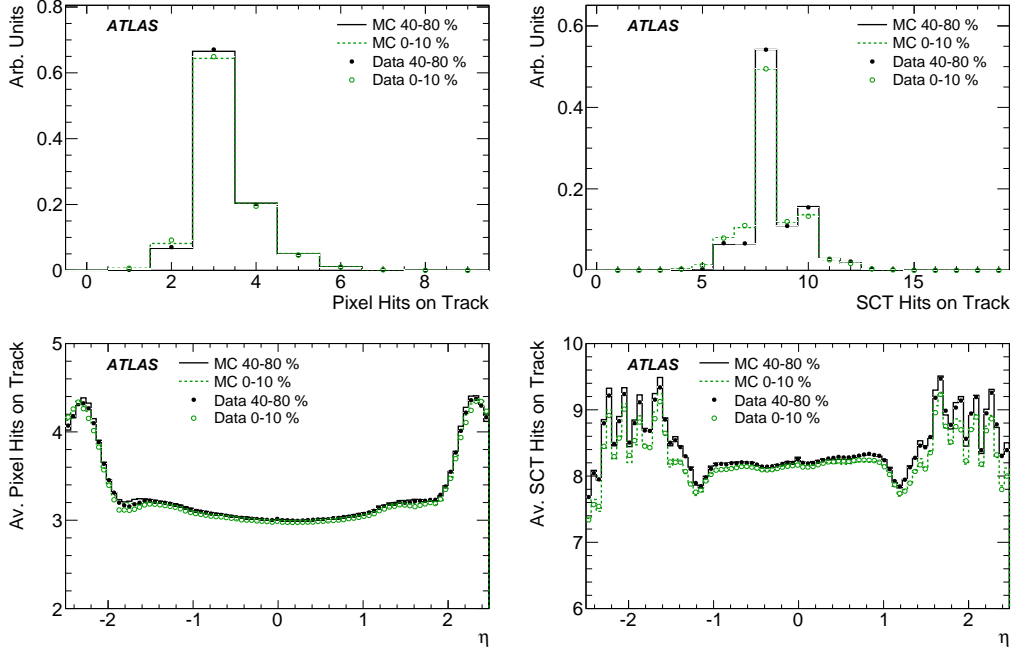


Figure 1: (top row) The number of Pixel (left) and SCT (right) hits on tracks for data (points with errors) and MC (histogram) for two different centrality bins: 0-10% (open/dotted) and 40-80% (closed/solid). (bottom row) The average number of Pixel (left) and SCT (right) hits as a function of η for MC and data in the same two centrality bins.

dense environment of the most central collisions is reasonably well modelled.

3. J/ψ production as a function of centrality

The oppositely-charged di-muon invariant mass spectra in the J/ψ region after the selection are shown in Figure 2. The number of $J/\psi \rightarrow \mu^+\mu^-$ decays is then found by a simple counting technique. The signal mass window is defined by the range 2.95–3.25 GeV. The background is derived from two mass sidebands, 2.4–2.8 GeV and 3.4–3.8 GeV, with a linear extrapolation. To determine the uncertainties related to the signal extraction, an alternative method based on a maximum likelihood fit with the mass resolution left as a free parameter is used as a cross check, as explained in section 3.1.

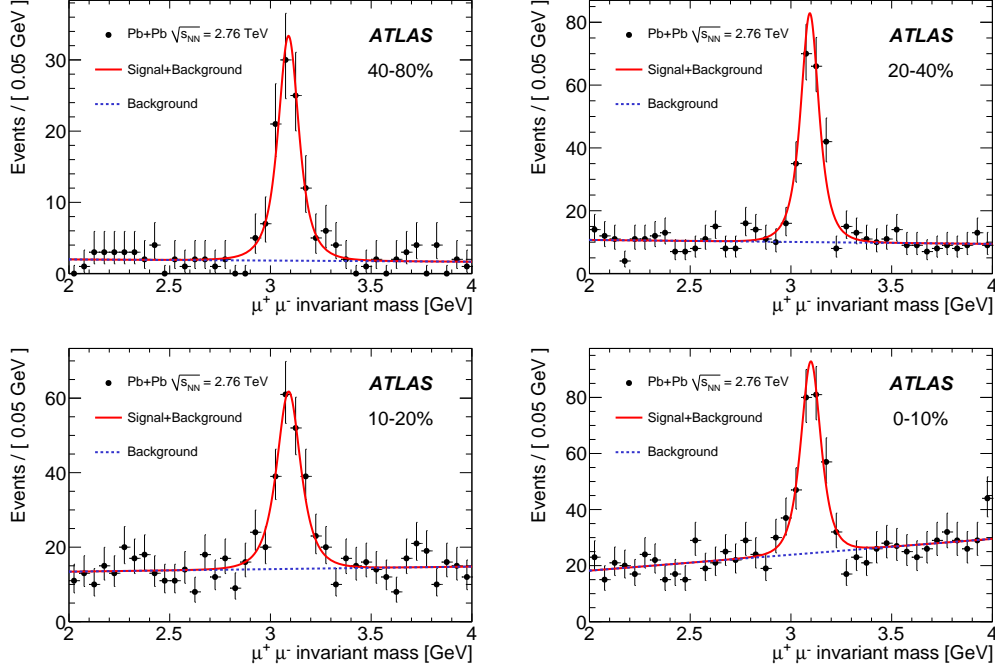


Figure 2: Oppositely-charged di-muon invariant mass spectra in the four considered centrality bins from most peripheral (40-80%) to most central (0-10%). The J/ψ yields in each centrality bin are obtained using a sideband technique. The fits shown here are used as a cross check.

Centrality-dependent efficiency corrections, derived from Monte Carlo events, are applied to the resulting signal yields. The number of J/ψ decays after background subtraction, but before any other correction, are listed in Table 1. With the chosen transverse momentum cuts on the decay muons, 80% of the reconstructed J/ψ have $p_T > 6.5$ GeV.

The measured J/ψ yields at different centralities are corrected by the reconstruction efficiency ϵ_c for $J/\psi \rightarrow \mu^+\mu^-$, derived from MC and parameterized in each centrality bin, and the width of the centrality bin, W_c , which represents a well-defined fraction of the minimum bias events. The corrected yield of J/ψ mesons is given by:

$$N_c^{\text{corr}}(J/\psi \rightarrow \mu^+\mu^-) = \frac{N^{\text{meas}}(J/\psi \rightarrow \mu^+\mu^-)_c}{\epsilon(J/\psi)_c \cdot W_c}. \quad (1)$$

The “relative yield” is defined by normalizing to the yield found in the most

Centrality	$N^{\text{meas}}(J/\psi)$	$\epsilon(J/\psi)_c / \epsilon(J/\psi)_{40-80}$	Systematic Uncertainty		
			Reco. eff.	Sig. extr.	Total
0-10%	190 ± 20	0.93 ± 0.01	6.8 %	5.2 %	8.6 %
10-20%	152 ± 16	0.91 ± 0.02	5.3 %	6.5 %	8.4 %
20-40%	180 ± 16	0.97 ± 0.01	3.3 %	6.8 %	7.5 %
40-80%	91 ± 10	1	2.3 %	5.6 %	6.1 %

Table 1: The measured numbers of J/ψ signal events per centrality bin before any correction, with their statistical errors, are listed in the second column. The relative efficiency corrections derived from the simulation are also shown, with the MC statistical error. The last columns give the experimental systematic uncertainties on the reconstruction efficiency and signal extraction, as well as the total uncertainty.

peripheral 40-80% centrality bin: $R_c = N_c^{\text{corr}} / N_{40-80\%}^{\text{corr}}$. Note that the uncertainties in the 40-80% bin are not propagated into this ratio for the more central bins. Finally, the “normalized yield” is defined by scaling the relative yield by the ratio R_{coll} of the mean number of binary collisions $N_{\text{coll},c}$, detailed in section 3.2, in each centrality bin to that for the most peripheral (40-80%) bin: $R_{cp} = R_c / R_{\text{coll}}$.

3.1. Experimental systematic uncertainties

Several experimental systematic effects are considered. These are grouped into those affecting the J/ψ reconstruction efficiency, and those from the extraction of the number of signal events from the di-muon mass spectra. Since this measurement only determines the relative yields as a function of centrality, only the centrality dependence of these effects is relevant. Any uncertainty on the absolute value cancels out in the ratio. The variation of the J/ψ reconstruction efficiency with centrality observed in simulation is mainly due to the larger occupancy in the ID. Because of the low occupancy in the MS by the primarily-soft tracks produced in heavy ion collisions, the fraction of muons from J/ψ decays with a reconstructed track in the MS is independent of centrality within the MC statistical uncertainty. On the other hand, to improve the reliability of the ID track reconstruction in the dense environment, rather stringent track quality requirements are made, relative to those defined for proton-proton collisions [15]. In particular, there must be at least nine silicon hits on each track, with no missing pixel hits and not more than one missing SCT hit, in both cases where such hits are expected. In order to evaluate systematic uncertainties, comparisons have

been made between the distributions of hits associated with tracks and missing hits between data and MC as a function of centrality. The differences between the fraction of tracks with associated or missing hits close to the track selection cuts have been used to derive the systematic uncertainties on the ID track reconstruction that range between 1 and 3% as a function of the centrality. These uncertainties are fully correlated for both muons from the J/ψ decay, resulting in a systematic uncertainty up to about 7% on the J/ψ reconstruction efficiency. As an additional cross-check, the ID reconstruction was run with looser cuts on the number of missing pixel and SCT hits, in order to study directly the number of tracks lost because of the cuts on these quantities. The resulting track losses, as a function of centrality in data and simulation, were compatible with the systematic uncertainties derived with the hit comparison method described above. Further cross-checks have been made by studying the matching between the MS and ID momentum measurements, and by examining variables such as the track multiplicity distribution in a cone of $\Delta R < 0.1$ (where $\Delta R^2 = \Delta\phi^2 + \Delta\eta^2$) around muon candidates, and by evaluating the relative momentum difference between the two independent measurements of the same muon candidate. The fraction of muons measured in the MS but not matched to any ID track has also been compared in data and MC as a function of centrality. All of these studies show that the MC reproduces well the behaviour of the data as a function of centrality. The relative statistical uncertainty on the MC efficiency corrections ranges between 1.6 and 3.2% and this is combined in quadrature with the other uncertainties.

To address the uncertainties associated with the J/ψ signal extraction, an independent method based on an unbinned maximum likelihood fit is used to evaluate the number of signal events from the di-muon mass spectra. An overall scale factor on the event-by-event mass resolution is a free parameter of the fit, allowing for possible variations of resolution with centrality. Two different background parameterizations are used, with either a first or second order polynomial. The maximum deviation of the fitted yield compared to the sideband subtraction method is taken as the systematic uncertainty on the signal extraction.

The systematic uncertainties from the different sources are listed in Table 1.

3.2. Definition of N_{coll}

The mean number of binary nucleon-nucleon collisions, N_{coll} , corresponding to each centrality bin was calculated using a Glauber Monte Carlo package that has been applied extensively at RHIC energies [16, 17]. The impact parameter is selected randomly event by event, and both the number of participating nucleons which undergo at least one inelastic collision (N_{part}) and the number of binary collisions (i.e. the total number of nucleon-nucleon collisions, N_{coll}) are calculated for each event. The primary experimental inputs to the Glauber calculation are the radius (R) and skin depth (a) parameters of the Wood-Saxon parameterization of the nuclear density ($\rho(r) = \rho_0/[1 + \exp((r - R)/a)]$), $R = 6.62 \pm 0.06$ fm and $a = 0.546 \pm 0.010$ fm, respectively [18], and the nucleon-nucleon inelastic cross-section, assumed to be $\sigma_{\text{inel}} = 64 \pm 6$ mb from an extrapolation of lower energy data. Using these parameters, the Glauber calculations give a total inelastic cross section of 7.6 barns, which is defined as the “geometric” cross section below.

Systematic uncertainties on the resulting R_{coll} values are estimated by separately varying R , a and σ_{inel} by one standard deviation. The variations of R and a are found to give results of the same magnitude but opposite sign, indicating that the uncertainties on the two parameters are correlated. However, they are conservatively treated as uncorrelated for the error analysis used in these studies.

Any possible variation in the fraction of the geometric cross section selected by the combination of trigger and event selection criteria, ε_{mb} , as a function of centrality must also be considered in evaluating systematic uncertainties on the lead-lead collision geometry, so that the centrality percentiles correspond to the correct fractions of the efficiency-corrected geometric cross section. The uncertainty is estimated by examining the distribution of $\Sigma E_{\text{T}}^{\text{FCal}}$ in the independent data sample selected by a random trigger and filtered by requiring a minimal amount of Inner Detector activity. The event selection criteria described above are also applied, with an additional requirement that both ZDCs see energies consistent with the presence of at least one neutron. This combination of vertex, MBTS and ZDC selections efficiently rejects photonuclear interactions [19]. The total selected fraction of the geometric cross section is estimated using a fit to the resulting $\Sigma E_{\text{T}}^{\text{FCal}}$ distribution, assuming the transverse energy in each event results from a superposition of participating nucleons and binary collisions (a similar as-

sumption to that used in Ref. [20]):

$$\Sigma E_T^{\text{FCal}} = E_T^{pp} \left\{ (1-x) \frac{N_{\text{part}}}{2} + x N_{\text{coll}} \right\}. \quad (2)$$

In this formula, E_T^{pp} is the value of ΣE_T^{FCal} when $N_{\text{part}} = 2$ and $N_{\text{coll}} = 1$ (the values for a single proton-proton collision) and x controls the relative contribution of participants and binary collisions in lead-lead events. An additional constant noise term is also included to account for the low energy part of the distribution. Distributions of ΣE_T^{FCal} are generated for 500k MC events and fitted to the data for a range of values of x (from 0.09 to 0.15), and also varying E_T^{pp} and the noise term. For all cases, the integral of the observed distribution in data accounts for around 98% of the best fit to the simulated distribution, with a variation of around 1%. This provides an estimate of the total event selection efficiency ε_{mb} relative to the geometric cross section. An absolute systematic error of $\pm 2\%$ is assigned to ε_{mb} with the positive range also accounting for the possible leakage of photonuclear events into the event sample used to obtain the ΣE_T^{FCal} distribution.

Centrality	R_{coll}	Uncertainty
0-10%	19.5	5.3 %
10-20%	11.9	4.7 %
20-40%	5.7	3.2 %
40-80%	1.0	—

Table 2: The correction factors R_{coll} , together with the relative systematic uncertainty, stated as a 1σ value.

The total systematic uncertainties on the ratios R_{coll} are evaluated by combining the variations with R , a , σ_{inel} and ε_{mb} , in quadrature. The values of R_{coll} and their systematic uncertainties are reported in Table 2. It should be noted that the estimate of ε_{mb} leads to correlations between the extracted values of N_{coll} , and thus the uncertainties on R_{coll} are also correlated bin-to-bin.

3.3. J/ψ yields

The relative J/ψ yields after normalization and efficiency corrections as in equation 1, R_c , are compared to the expected R_{coll} values in the left panel of Figure 3. The yield errors are computed by adding the statistical and

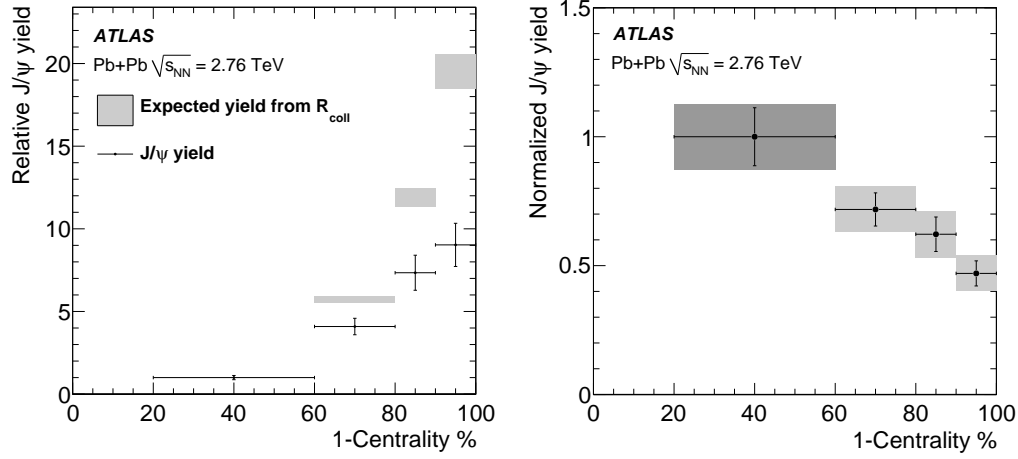


Figure 3: (left) Relative J/ψ yield as a function of centrality normalized to the most peripheral bin (black dots with errors). The expected relative yields from the (normalized) number of binary collisions (R_{coll}) are also shown (boxes, reflecting 1σ systematic uncertainties). (right) Value of R_{cp} , as described in the text, as a function of centrality. The statistical errors are shown as vertical bars while the grey boxes also include the combined systematic errors. The darker box indicates that the 40-80% bin is used to set the scale for all bins, but the uncertainties in this bin are not propagated into the more central ones.

systematic uncertainties in quadrature. A clear difference is observed as a function of centrality between the measured relative J/ψ yield and the prediction based on R_{coll} , indicating a deviation from the simplest expectation based on QCD factorization. The ratio of these two values, R_{cp} , is shown as a function of centrality in the right panel of Figure 3. The data points are not consistent with their average, giving a $P(\chi^2, N_{\text{DOF}})$ value of 0.11% with three degrees of freedom, computed conservatively ignoring any correlations among the systematic uncertainties. Instead, a significant decrease of R_{cp} as a function of centrality is observed.

4. Z production as a function of centrality

Z candidates are selected by requiring a pair of oppositely charged muons with $p_T > 20$ GeV and $|\eta| < 2.5$ [21]. An additional cosmic ray rejection cut on the sum of the pseudorapidities of the two muons, $|\eta_1 + \eta_2| > 0.01$, is also applied. The invariant mass distribution of the selected pairs is shown in the

Centrality	$N(Z)$	$\epsilon(Z)_c/\epsilon(Z)_{40-80}$
0-10%	19	0.99 ± 0.01
10-20%	5	0.97 ± 0.01
20-40%	10	0.98 ± 0.01
40-80%	4	1

Table 3: The number of Z events per centrality bin and the relative efficiency corrections derived from the simulation.

left panel of Figure 4. With this selection, 38 Z candidates are retained in the signal mass window of 66 to 116 GeV. The background after this selection is expected to be below 2%, and is not corrected for in the result. The number of Z events in each centrality bin is given in Table 3.

The R_{cp} variable for the Z candidates is computed in the same way as for the J/ψ sample. The relative efficiency corrections determined from dedicated MC samples are given in Table 3. For high transverse momentum tracks, the reconstruction is expected to perform as well as or better than in the low p_T regime characteristic of the J/ψ study. For this reason, the same systematic uncertainties as for the J/ψ results have been applied to the Z relative yield measurements. Several cross-checks have been performed to support this assumption. In addition to the tracks reconstructed with the combined ID and MS information, tracks reconstructed by the MS alone have been checked, and only one additional candidate was found. This candidate has been inspected and an ID track was in fact found but with too few hits to pass the stringent reconstruction requirements. The Z selection was also applied to same charge muon pairs, and no candidates were selected within the 66–116 GeV mass window. To control the residual background from cosmic rays, the distribution of the difference of the transverse impact parameters of the two muons from Z candidates was examined and found to be compatible with that expected for collision muons.

The measured Z yields are displayed in the right panel of Figure 4, normalized to the yield in the most peripheral bin and to the number of binary collisions (R_{cp}). Although, within the large statistical uncertainty, they appear to be compatible with a linear scaling with the number of binary collisions, the low statistics preclude drawing any conclusion.

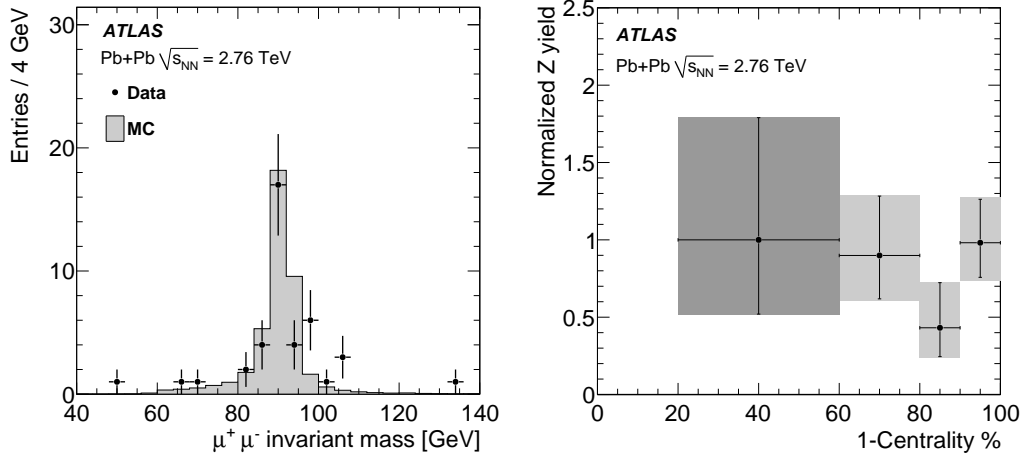


Figure 4: The di-muon invariant mass (left) after the selection described in the text. The value of R_{cp} (right) computed with the 38 selected Z candidates. The statistical errors are shown as vertical bars while the grey boxes also include the combined systematic errors. The darker box indicates that the 40-80% bin is used to set the scale for all bins, but the uncertainties in this bin are not propagated into the more central ones.

5. Conclusion

The first results on J/ψ and $Z \rightarrow \mu^+\mu^-$ relative yields measured in lead-lead collisions obtained with the ATLAS detector at the LHC, have been presented. In a sample of events with oppositely charged muon pairs with a transverse momentum above 3 GeV and with $|\eta| < 2.5$, a centrality dependent suppression is observed in the normalized J/ψ yield. The relative yields of the 38 observed Z candidates as a function of centrality are also presented, although no conclusion can be inferred about their scaling with the number of binary collisions.

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